

# QUESTIONS BANK

## BBS01T1002 SEMICONDUCTOR PHYSICS

### CAT-1 (Syllabus)

#### Unit -1 : Quantum and Band Theory of electron

Quantum free electron theory, Fermi Dirac distribution function and Fermi level, density of states  
Energy band in solids, E-K diagram and Brillouin zone.

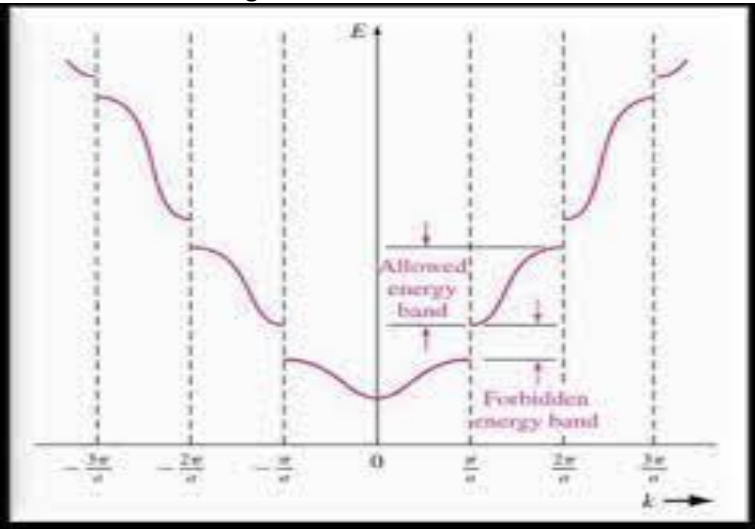
#### Unit -2 : Semiconductor

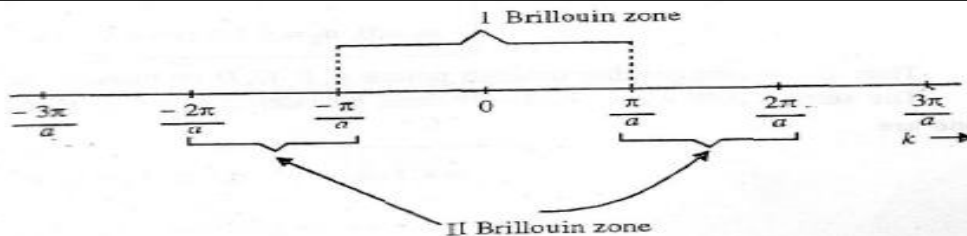
Types of semiconductor, Fermi level in semiconductor, effect of carrier concentration and  
temperature on Fermi- level, direct-indirect band gap semiconductors, compound semiconductors

#### Unit-1\_ (CO1): Identify the energy band in solids and electron occupation probability

SOLUTION	S. N o.
<p>Q-1. Find the least energy of an electron moving in one dimensional infinitely high potential box of width 0.05 nm. [Given Planck's Constant (<math>h</math>) = <math>6.625 \times 10^{-34}</math> J.s. and mass of electron (<math>m</math>) = <math>9.1 \times 10^{-31}</math> kg. ]</p> <p><b>Solution:</b> We know that energy of electron is Given by [Particle in Box]  <math>E_n = n^2 h^2 / 8mL^2</math>, where <math>n=1,2,3,\dots</math> etc.                      Given <math>L = 0.05</math> nm but <math>1\text{nm} = 10^{-9}</math> m                      For least energy <math>n=1</math>                      Therefore, <math>E_1 = h^2 / 8mL^2</math> now put <math>h = 6.625 \times 10^{-34}</math> and <math>m = 9.1 \times 10^{-31}</math> kg. and <math>L = 0.05 \times 10^{-9}</math> m  <math>E_1 = \{6.625 \times 10^{-34}\}^2 / 8 \times 9.1 \times 10^{-31} \times [5 \times 10^{-11}]^2</math>  <math>E_1 = 0.0241157 \times 10^{-15}</math> jule  <math>E_1 = 0.0241157 \times 10^{-15} / 1.6 \times 10^{-19}</math>  <math>E_1 = 0.015072 \times 10^4</math>  <b><math>E_1 = 150.7</math> eV</b></p>	1
<p>Q-2. An electron is bound in a one dimensional potential box which has a width <math>2.5 \times 10^{-10}</math> m. Assuming the height of the box to be infinite, calculate the lowest two permitted energy values of the electron. [Given Planck's Constant (<math>h</math>) = <math>6.625 \times 10^{-34}</math> J.s. and mass of electron (<math>m</math>) = <math>9.1 \times 10^{-31}</math> kg.]</p> <p><b>Solution:</b> We know that energy of electron is Given by [Particle in Box]  <math>E_n = n^2 h^2 / 8mL^2</math>, where <math>n=1,2, 3,\dots</math> etc.                      Given <math>L = 2.5 \times 10^{-10}</math> m.                      For lowest two energy <math>n=1</math> &amp; <math>n=2</math> for <math>n=1</math> Energy <math>E_1</math> and for <math>n=2</math> energy <math>E_2 = 4E_1</math>                      Therefore, <math>E_1 = h^2 / 8mL^2</math> now put <math>h = 6.625 \times 10^{-34}</math> and <math>m = 9.1 \times 10^{-31}</math> kg. and <math>L = 2.5 \times 10^{-10}</math> m.  <math>E_1 = \{6.625 \times 10^{-34}\}^2 / 8 \times 9.1 \times 10^{-31} \times [2.5 \times 10^{-10}]^2</math>  <math>E_1 = 0.0964629 \times 10^{-17}</math> jule  <math>E_1 = 0.0602893 \times 100</math>  <math>E_1 = 6.02893</math> eV                      &amp; <math>E_2 = 4 \times 6.02893</math>  <math>E_2 = 24.11</math> eV  <b>Lowest two permitted energy are = 6.02 eV and 24.11 eV</b></p>	2
<p>Q-3. Find the minimum energy of an electron moving in one dimension in an infinitely high potential box of width <math>1\text{\AA}</math>. [Given Planck's Constant (<math>h</math>) = <math>6.625 \times 10^{-34}</math> J.s. and mass of electron (<math>m</math>) = <math>9.1 \times 10^{-31}</math> kg.]</p> <p><b>Solution:</b> We know that energy of electron is Given by [Particle in Box]  <math>E_n = n^2 h^2 / 8mL^2</math>, where <math>n=1,2, 3,\dots</math> etc.                      Given <math>1\text{\AA}</math>. But <math>1\text{\AA} = 1 \times 10^{-10}</math> m                      For minimum energy <math>n=1</math> we have to find <math>E_1</math></p>	3

<p>Therefore, <math>E_1 = h^2/8mL^2</math> now put <math>h = 6.625 \times 10^{-34}</math> and <math>m = 9.1 \times 10^{-31}</math> kg. and <math>L = 1 \times 10^{-10}</math> m.</p> <p><math>E_1 = \{6.625 \times 10^{-34}\}^2 / 8 \times 9.1 \times 10^{-31} \times [1 \times 10^{-10}]^2</math></p> <p><math>E_1 = 0.602893 \times 10^{-17}</math> jule</p> <p><math>E_1 = 0.602893 \times 10^{-17} / 1.6 \times 10^{-19}</math></p> <p><b><math>E_1 = 37.68</math> eV</b></p> <p><b>Minimum energy of electron = 37.68 eV</b></p>	
<p>Q-4. The Fermi Energy for a given solid is 5.0 eV at <math>T=0</math>K. What is the average energy of the electron in the metal at 0 K?</p> <p><b>Solution:</b> We know that average energy of electron at <math>T=0</math>K is Given by</p> <p><math>E_{av} = 3E_F / 5</math>, where <math>E_F</math> is Fermi energy of electron</p> <p>Therefore, <math>E_{av} = 3 \times 5 / 5 = 3</math> eV</p> <p><b>Average energy of electron = 3.0 eV</b></p>	4
<p>Q-5. The Fermi level for potassium is 2.0 eV. Calculate the velocity of the electrons at the Fermi level.</p> <p><b>Solution:</b> We know that</p> <p><math>kBT_F = E_F</math> i.e. <math>TF = E_F / k_B</math></p> <p><math>\frac{1}{2} mv_F^2 = kBT_F</math> i.e. <math>v_F = (k_B T_F / m)^{1/2}</math></p> <p><math>v_F = (E_F / m)^{1/2}</math></p> <p><b><math>v_F = (2 \times 1.6 \times 10^{-19} / 9.1 \times 10^{-31})^{1/2}</math></b></p> <p><math>v_F = 0.351648 \times 10^6</math></p> <p><math>v_F = 3.516 \times 10^5</math> m/s</p> <p><b>Velocity of electron = <math>3.516 \times 10^5</math> m/s</b></p>	5
<p>Q-6. What is the value of Fermi-Dirac distribution function for <math>T=0</math>, when (i) energy is greater than Fermi Energy and (ii) when energy is less than Fermi Energy.</p> <p><b>Solution:</b> Fermi function describe the probable distribution of electron in the energy states, mathematically the Fermi-function is given by</p> $f(E) = \frac{1}{1 + \exp[(E - E_F) / k_B T]}$ <p>when (i) energy is greater than Fermi Energy i.e. <math>E &gt; E_F</math>, <math>f(E) = 0</math></p> <p>and (ii) when energy is less than Fermi Energy i.e. <math>E &lt; E_F</math>, <math>f(E) = 1</math></p>	6
<p>Q-7. Define the Fermi Energy. If the Fermi energy is 10eV, calculate the mean energy of electron at 0 Kelvin.</p> <p><b>Solution:</b> The Fermi energy is a concept in quantum mechanics usually refers to the energy difference between the highest and lowest occupied single-particle states in a quantum system of non-interacting fermions at absolute zero temperature.</p> <p>Average energy of electron at <math>T=0</math>K is given by</p> <p><math>E_0 = 3E_F / 5</math></p> <p><math>E_0 = 3 \times 10 / 5 = 4</math> eV</p> <p><b>Fermi energy of electron = 4.0 eV</b></p>	7
<p>Q-8. Write Schrodinger's time-independent equation for matter waves. Explain the physical significance of the wave function?</p> <p><b>Solution:</b> Schrodinger wave equation (time-independent form) for matter waves In one dimension is written as</p> $\frac{d^2 \psi_n}{dx^2} + \frac{2m(E_n - V)}{\hbar^2} \psi_n = 0$ <p>Physical Significance of Wave-function: By <a href="#">analogy</a> with waves such as those of sound, a wave function, designated by the Greek letter psi, <math>\Psi</math>, may be thought of as an expression for the amplitude of the particle wave (or de Broglie wave), although for such waves amplitude has no physical significance. The square of the wave function, <math>\Psi^2</math>, however, does have physical significance: the probability of finding the particle described by a specific wave function <math>\Psi</math> at a given point and time is proportional to the value of <math>\Psi^2</math>.</p>	8

<p>Since the probability of a particle being somewhere in space is unity, the Integration of the wave-function over all space leads to a probability of 1. That is, the wave-function is normalized:</p> $\int_{-\infty}^{\infty} \Psi^*(x, t) \Psi(x, t) dx = 1$ <p>Every acceptable wave function can be normalized by multiplying it by an appropriate constant</p>	
<p>Q-9. Explain the idea of wave function for a quantum particle. Write the basic characteristics of well-behaved wave function</p> <p><b>Solution: wave function</b>, in <a href="#">quantum mechanics</a>, variable quantity that mathematically describes the <a href="#">wave</a> characteristics of a <a href="#">particle</a>. The value of the wave <a href="#">function</a> of a particle at a given point of space and time is related to the likelihood of the particle's being there at the time. By <a href="#">analogy</a> with waves such as those of sound, a wave function, designated by the Greek letter psi, <math>\Psi</math>, may be thought of as an expression for the amplitude of the particle wave (or de Broglie wave), although for such waves amplitude has no physical significance. The square of the wave function, <math>\Psi^2</math>, however, does have physical significance: the probability of finding the particle described by a specific wave function <math>\Psi</math> at a given point and time is proportional to the value of <math>\Psi^2</math>.</p> <p>Since the probability of a particle being somewhere in space is unity, the Integration of the wave-function over all space leads to a probability of 1. That is, the wave-function is normalized:</p> $\int_{-\infty}^{\infty} \Psi^*(x, t) \Psi(x, t) dx = 1$ <p>Every acceptable wave function can be normalized by multiplying it by an appropriate constant</p> <p><b>Characteristics for a suitable wave-function-(Well-Behaved Wave Functions)</b></p> <p>In order for <math>\Psi(x; t)</math> to represent a viable physical state, certain conditions are required:</p> <ol style="list-style-type: none"> <li>1. The wave-function must be a single-valued function of the spatial Coordinates. (single probability for being in a given spatial interval)</li> <li>2. The first derivative of the wave-function must be continuous so that the second derivative exists in order to satisfy the Schrodinger equation.</li> <li>3. The wave-function cannot have an infinite amplitude over a finite interval. This would preclude normalization over the interval.</li> </ol>	9
<p>Q-10. Draw the E-K diagram of a semiconductor based on band theory of solids. Explain the Brillouin zones in a solid.</p> <p><b>Solution:</b> the E-K diagram of a semiconductor is shown below</p>  <p>The diagram shows Energy (E) on the vertical axis and wave vector (k) on the horizontal axis. The horizontal axis is marked with values <math>-\frac{3\pi}{a}</math>, <math>-\frac{2\pi}{a}</math>, <math>-\frac{\pi}{a}</math>, 0, <math>\frac{\pi}{a}</math>, <math>\frac{2\pi}{a}</math>, and <math>\frac{3\pi}{a}</math>. Vertical dashed lines represent the boundaries of the Brillouin zones. The energy bands are shown as continuous curves within the zones, with gaps between them. The regions with bands are labeled 'Allowed energy band' and the regions without bands are labeled 'Forbidden energy band'.</p>	1 0



In one dimensional periodic lattice, the energy discontinuities occur when the wave number  $k$  satisfies the condition  $k = n\pi/a$  where  $n$  is a +ve or -ve integer. If we consider a line Fig 6, representing  $k$  values divided into energy discontinuities into segments of length  $\pm\pi/a$ , then these line segments are known as Brillouin zones

$$-\frac{\pi}{a} < k < +\frac{\pi}{a}$$

The first segment is called the First Brillouin zone.

$-\frac{2\pi}{a} < k < -\frac{\pi}{a}$  and  $k = \frac{\pi}{a}$  to  $\frac{2\pi}{a}$ , This zone is called second Brillouin zone

Q-11. What would be the band structure if the barrier strength is extremely high or negligible? Justify your answer with a suitable diagram.

**Solution:** In the Kronig-Penney model/From Band Theory of Solids, We know that

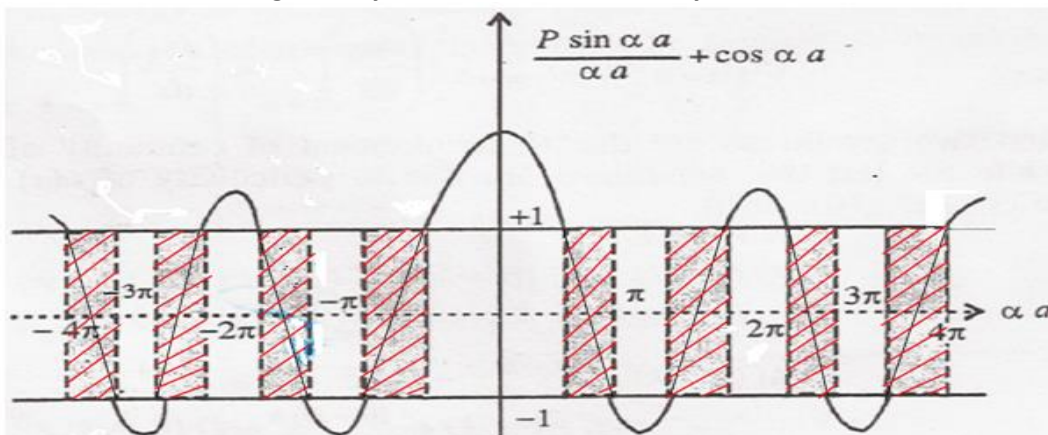


Fig.3: Plot the function  $\left(\frac{P \sin \alpha a}{\alpha a} + \cos \alpha a\right)$  for  $P=3\pi/2$  where allowed energy band is represented by the shaded region

$$P \frac{\sin \alpha a}{\alpha a} + \cos \alpha a = \cos ka \quad \text{----- (7)}$$

where  $P = \frac{m V_0}{\hbar^2} a b$

$P$  is a measure of the quantity  $V_0 b$ , which is the area of potential barrier, called barrier strength

- Equation (7) is satisfied only for those values of  $\alpha a$  for which left hand side lies between +1 and -1 this is because R.H.S must lie in the range +1 to -1. Such values of  $\alpha a$  will, therefore, represent the wave like solutions and are accessible. The other values of  $\alpha a$  will be inaccessible.
- In Fig. 3, the part of the vertical axis lying between the horizontal lines represents the range acceptable. As  $\alpha^2$  is proportional to the energy  $E$ , the abscissa ( $\alpha a$ ) will be a measure of the energy

- Clearly there are regions for  $\alpha a$  where the value of  $\left(\frac{P \sin \alpha a}{\alpha a} + \cos \alpha a\right)$  does not lie between -1 and +1. For these values of  $\alpha a$  and hence of energy  $E$ , no solutions exist. Such regions of energy are prohibited and are called forbidden bands.

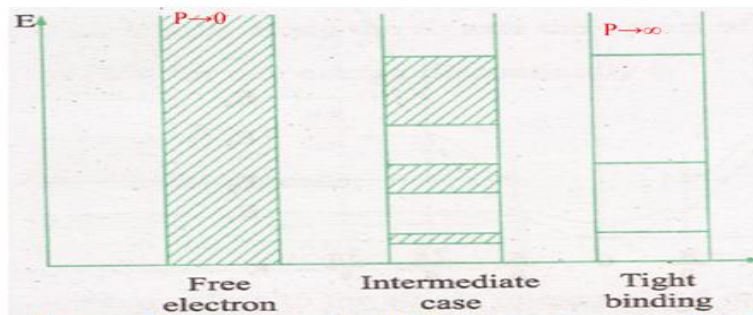


Fig. 4 Energy level structure for differentiating degrees of binding

The energy spectrum of the electron consists of alternate regions of allowed energy and forbidden energy

- i. The width of the allowed energy band increases as the value of  $\alpha a$  (i.e., energy) increases.
- ii. It is to be noted that  $P$  is a measure of the potential barrier strength.

Case 1: When  $P \rightarrow \infty$ , corresponding to a infinitely deep potential well, the electron can be considered as confined into a single potential well. This case applies to crystals where the electrons are very tightly bound

Equation (7) has the solutions only if  $\sin \alpha a = 0$  or,  $\alpha a = n\pi$ ,

This is the equation of energy levels of particle in a constant potential box of atomic dimension

This is the equation of energy levels of particle in a constant potential box of atomic dimension. The allowed energy bands are compressed into energy levels and the energy spectrum is a line spectrum (As in Fig.4).

Case 2 : When  $P \rightarrow 0$ , corresponds to no barrier, the electron can be considered to be moving freely through the potential wells.

$$\cos \alpha a = \cos ka \text{ i.e., } \alpha = k \text{ or } \alpha^2 = k^2$$

$$\frac{2mE}{\hbar^2} = k^2$$

$$\frac{\hbar^2 k^2}{2m} = \frac{P^2}{2m}, \quad [As \ k = \frac{2\pi}{\lambda}, \lambda = \frac{h}{p}]$$

$$E = \frac{\hbar^2 k^2}{2m} = \frac{p^2}{2m}, \quad [As \ k = \frac{2\pi}{\lambda}, \lambda = \frac{h}{p}]$$

which is appropriate to the completely free particle.

Case 3 : Between these two extreme limits, intermediate case, the position and the width of the allowed and forbidden bands for any value of  $P$  are obtained by drawing vertical lines in Fig. 5, the shaded areas corresponds to the allowed bands (Fig. 4 and Fig.5). Thus by varying  $P$  from zero to infinity we cover the whole range, from the completely free electron to the completely bound electron.

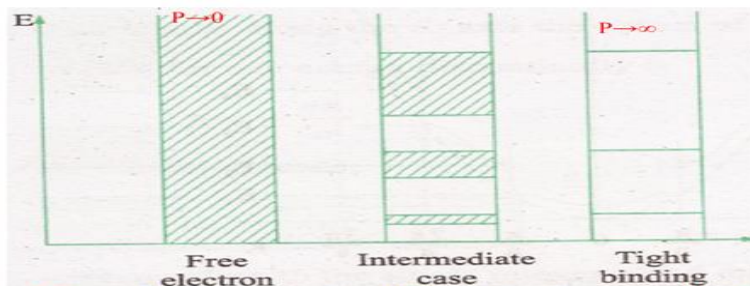


Fig. 4 Energy level structure for differentiating degrees of binding

Q-12. Define the density of energy state in a solid. Find the expression for density of states.

**Solution:**



1. The allowed energy for 1D potential box,  $E_n = \frac{h^2 n^2}{8mL^2}$

where  $m$  is mass of particle,  $L$  is the length of potential box and  $n$  are positive integers like 1, 2, 3, 4, 5....

The allowed energy for 3D cubical potential box

$$E = \frac{h^2}{8mL^2} (n_x^2 + n_y^2 + n_z^2) \quad \text{-----(1)}$$

where  $n_x$ ,  $n_y$  and  $n_z$  are three quantum numbers which are only positive integer value.

where  $n^2 = n_x^2 + n_y^2 + n_z^2$  -----(2)

$$E = \frac{h^2}{8mL^2} n^2$$

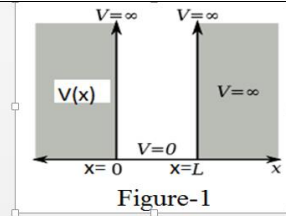


Figure-1

The potential energy within the 1D crystal or box is

$$V(x) = 0 \quad \text{for } 0 < x < L$$

$$V(x) = \infty \quad \text{for } x \leq 0 \text{ and } x \geq L$$

Density of energy states is defined by the number of allowed energy states present in unit volume at a given energy.

Since even at highest energy, the difference between neighbouring energy levels is as small as  $10^{-6}$  eV, in a macroscopically small energy interval  $dE$  there are still many discrete energy levels. So the concept of density of energy states is introduced.

The Fermi energy,  $E_F$  is the energy of the highest filled level at absolute zero.

- Number of energy states with a particular value of  $E$ , depends on the how many combinations of the quantum number ( $n_x$ ,  $n_y$ ,  $n_z$ ) result in the same value  $n$ . [From equation (1)]

$$E = \frac{h^2}{8mL^2} (n_x^2 + n_y^2 + n_z^2)$$

- A space of points is constructed with the values of  $n_x$ ,  $n_y$ ,  $n_z$
- Each point ( $n_x$ ,  $n_y$ ,  $n_z$ ) with positive integer values of coordinates represents an energy state.
- A radius vector  $n$  from the origin is drawn to a point  $n_x$ ,  $n_y$ ,  $n_z$  in this space and according to equation (2) [ $n^2 = n_x^2 + n_y^2 + n_z^2$ ] all points on the surface of a sphere of radius  $n$  will have the same energy.
- $n$  represents a vector to a point  $n_x$ ,  $n_y$ ,  $n_z$  in three-dimensional space.
- In this space every integer specifies a state, that is a unit cube contains exactly one state.
- The number of states in any volume is just equal to the numerical value of the volume expressed in units of cubes of lattice parameters.

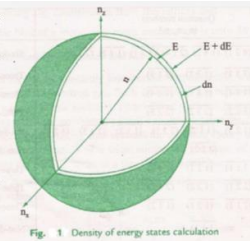


Fig. 1 Density of energy states calculation

Number of available states within a sphere of radius  $n = \frac{1}{8} \left( \frac{4}{3} \pi n^3 \right)$

Number of available states within a sphere of radius  $(n+dn) =$

$$\frac{1}{8} \left[ \frac{4}{3} \pi (n + dn)^3 \right]$$

The factor  $1/8$  accounts for the fact that only positive integers are allowable and thus only one octant of the sphere alone be considered.

$$\begin{aligned} \text{Number of available states within } n \text{ to } (n+dn) &= \frac{1}{8} \frac{4}{3} \pi [(n+dn)^3 - n^3] \\ &\cong \frac{\pi}{6} (3n^2 dn) \end{aligned}$$

[Neglecting higher order terms of  $dn$ ]

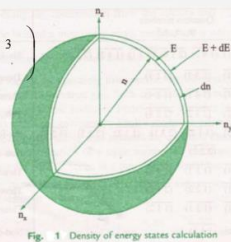


Fig. 1 Density of energy states calculation

Number of available states within  $n$  to  $(n+dn)$   $= \frac{\pi}{2} n^2 dn = \frac{\pi}{4} n (2n dn)$

From Equation (1),  $n^2 = \frac{8mL^2}{h^2} E$   $n = \left[ \frac{8mL^2}{h^2} \right]^{1/2} E^{1/2}$

$$2n \, dn = \left[ \frac{8mL^2}{h^2} \right] dE$$

Number of available states within  $E$  to  $(E+dE)$ ,

$$Z'(E) \, dE = \frac{\pi}{4} \left[ \frac{8mL^2}{h^2} \right]^{1/2} E^{1/2} \left[ \frac{8mL^2}{h^2} \right] dE$$

$$Z'(E) \, dE = \frac{\pi}{4} \left[ \frac{8mL^2}{h^2} \right]^{3/2} E^{1/2} dE$$

It should be remembered that the Pauli's exclusion principle permits **two electrons in each state**, so that the number of energy levels actually available are

$$Z'(E) \, dE = 2 \frac{\pi}{4} \left[ \frac{8mL^2}{h^2} \right]^{3/2} E^{1/2} dE$$

$$Z'(E) \, dE = \frac{\pi}{2} \left[ \frac{8mL^2}{h^2} \right]^{3/2} E^{1/2} dE \quad \text{-----(4)}$$

**Density of energy states having energy values lying between  $E$  and  $E+dE$ ,**

$$Z(E) \, dE = Z'(E) \, dE / V = \frac{\pi}{2} \left[ \frac{8m}{h^2} \right]^{3/2} E^{1/2} dE \quad [\text{As } L^3 = V]$$

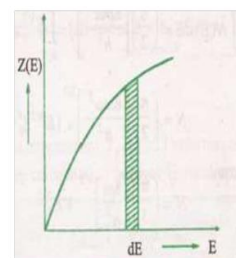


Fig 2: Density of states as a function of electron energy

**The last expression is the formula of density of energy states.**

Q-13. An electron is in motion along a line between  $x=0$  and  $x=L$  with zero potential energy. At points for which  $x \leq 0$  and  $x \geq L$ , the potential energy is infinite. The wave function for the particle in the  $n^{\text{th}}$  state is given by  $\psi_n = A \sin(n\pi x/L)$ . Find the expression for the normalized wave function.

**Solution:** The wave function for the particle in the  $n^{\text{th}}$  state is given by  $\psi_n = A \sin(n\pi x/L)$ .

It is certain that the particle is somewhere inside the box. The constant  $A$  in the given equation is determined by using this information that the probability of finding an electron somewhere on the line is unity, i.e.

$$\int_0^L \psi_n^* \psi_n \, dx = 1$$

This is called as normalization condition. We get

$$A^2 \int_0^L \sin^2\left(\frac{n\pi}{L}x\right) dx = 1, \text{ or}$$

$$A^2 \int_0^L 1 - \cos\left(\frac{2n\pi}{L}x\right) dx = 2, \text{ or } A^2 \int_0^L dx = 2, \text{ or}$$

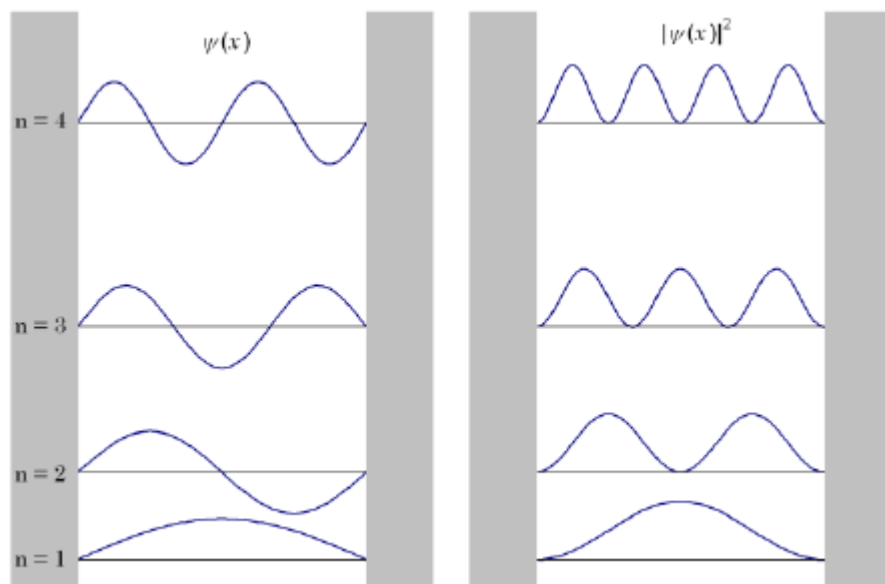
$$A = \sqrt{\frac{2}{L}}$$

The energy levels and the wave functions corresponding to  $n=1, 2, 3$ , and  $4$  are shown

So, we get the normalized wave function as

$$\psi_n = \left(\frac{2}{L}\right)^{1/2} \sin\left(\frac{n\pi}{L}x\right)$$

Where  $n=1,2,3,4,\dots$  etc.

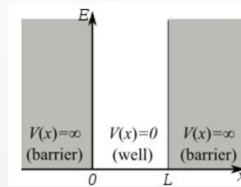


Q-14. An electron is in motion along a line between  $x=0$  and  $x=L$  with zero potential energy. At points for which  $x \leq 0$  and  $x \geq L$ , the potential energy is infinite. Solving Schrodinger's equation, obtain energy Eigen values

1  
4



Consider an electron of mass 'm' which is bound to move in a one dimensional crystal of length 'L'. The electron is prevented from leaving the crystal by the presence of a large potential energy barrier at its surfaces. Although the barriers extend over a few atomic layers near the surface, these are taken infinitely large for the sake of simplicity. The problem is identical to that of an electron moving in a one – dimensional potential box which is represented by a line and is bounded by infinite potential energy barriers as shown in figure



The potential energy within the crystal or box is assumed to be zero. Thus, we have

$$\begin{aligned} V(x) &= 0 & \text{for } 0 < x < L \\ V(x) &= \infty & \text{for } x \leq 0 \text{ and } x \geq L \end{aligned} \quad \text{-----(1)}$$

The wave function  $\psi_n$  of the electron occupying the nth state is determined from the solution of the Schrodinger equation, i.e.

$$\frac{d^2\psi_n}{dx^2} + \frac{2m(E_n - V)}{\hbar^2} \psi_n = 0 \quad \text{-----(2)}$$

Where  $E_n$  represents the kinetic energy of the electron in the nth state and V is its potential energy. Since  $V=0$  inside the box Equation (2) becomes

$$\frac{d^2\psi_n}{dx^2} + \frac{2mE_n}{\hbar^2} \psi_n = 0 \quad \text{----- (3)}$$

**Solution:**

The general solution of this equation is

$$\psi_n = A \sin(kx) + B \cos(kx) \quad \text{-----(4)}$$

Where A and B are arbitrary constants to be determined from the boundary conditions and k is given by

$$k = \sqrt{\frac{2mE_n}{\hbar^2}} \quad (5)$$

The boundary conditions are,  $\psi_n = 0$  when  $x = 0$  and  $\psi_n = 0$  when  $x = L$

For  $x = 0$  equation (4) gives  $B = 0$  and the solution (4) becomes

$$\psi_n = A \sin(kx) \quad (6)$$

Also  $\psi_n = 0$  when  $x = L$ , therefore, equation (6) yields

$$\sin(KL) = 0$$

Since A cannot be zero as this will make the wave function zero everywhere. Therefore

$$\begin{aligned} \sin(KL) &= 0 \text{ hence } KL = n\pi \\ \text{Or } K &= n\pi/L \end{aligned}$$

Where  $n = 1, 2, 3, 4, 5, \dots$ . Thus the expression (6) for the allowed wave function becomes

$$\psi_n = A \sin\left(\frac{n\pi}{L}x\right) \quad (8)$$

The allowed energy can be obtained from equations (5) and (7) as

$$\begin{aligned} E_n &= \frac{\hbar^2}{2m} \left(\frac{n\pi}{L}\right)^2 \\ E_n &\propto n^2 \end{aligned} \quad (9)$$

**$E_n = n^2 h^2 / 8mL^2$  , where  $n=1,2,3,\dots$  etc.**

**This is the expression of energy Eigen Values**

Q-15. Explain the energy band in solids and classify the materials based on energy gap.

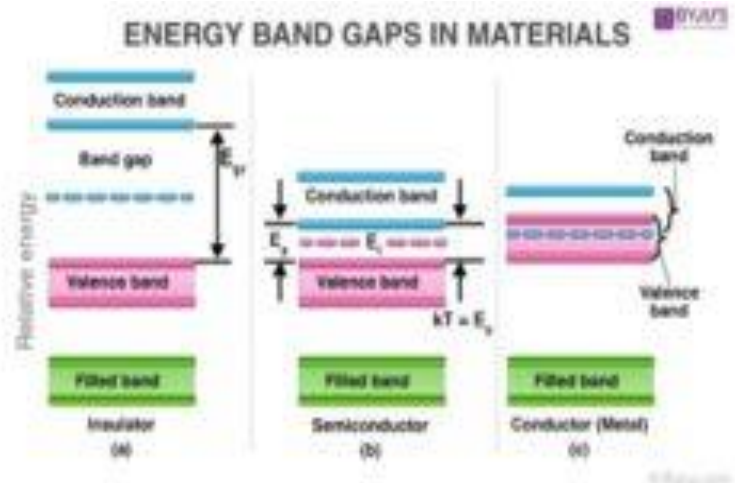
**Solution:** The band theory of solids is different from the others because the atoms are arranged very close to each other such that the energy levels of the outermost orbital electrons are affected. But the energy level of the innermost electrons is not affected by the neighbouring atoms.

The three energy bands in solids are

- Valence band
- Conduction band
- Forbidden band

#### Bond theory solids

- In atoms, electrons are filled in respective energy orbits following Pauli's exclusion principle.
- In molecules, Two atomic orbitals combine together to form a molecular orbit with two distinct energy levels.
- In solids,  $10^{23}$  stacked up lines confined in a tiny space would look like a band. Thereby forming energy continuum called energy bands.
- This theory helps to visualise the difference between conductor, semiconductors and insulator by plotting available energies for an electron in a material.



#### Conductors:

Metals are conductors in which there is no forbidden energy gap between the conduction band (CB) and valence band (VB). No extra energy required to transfer the electron from VB to CB.

#### Semiconductors:

In a semiconductor, the valence band is completely filled with electrons while the conduction band is empty. The energy gap between the bands is less. For electrons to jump from the valence band to the conduction band, room temperature needs to be maintained. If the temperature is 0K, there is no transfer of electrons from the valence band to the conduction band.

#### Insulators:

In insulators, the valence band is completely filled while the conduction band is empty. This results in a large energy gap. Since the energy gap between the conduction band and the valence band is more, there is no movement of electrons from the valence band to the conduction band.

Solids can be categorized into three main groups on the basis of band gaps as

- A. Insulators
- B. Semiconductor
- C. Conductor.

### A. Insulators

- The forbidden energy gap ( $E_g$ ) is greater than 3eV
- do not conduct electricity
- number of electrons is just enough to completely fill a number of allowed energy bands.
- Above these bands there exists a series of completely empty bands.
- At ordinary temperatures electron can't be thermally excited across this gap from the valence band to the conduction band.
- As the bands are either completely filled or empty, no electric current flow.

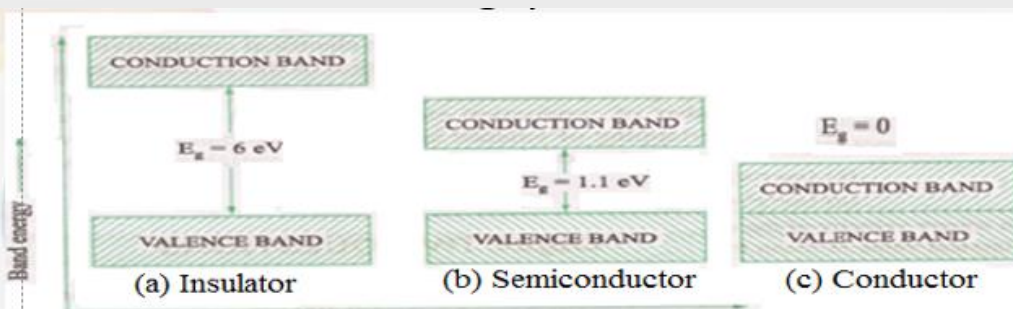
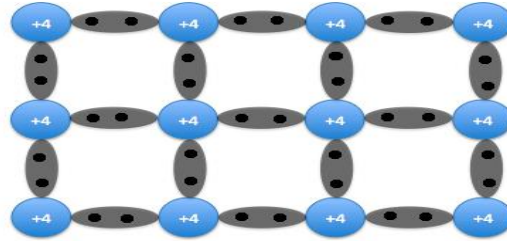


Fig. 1 Energy band diagram of (a) Insulator, (b) Semiconductor and (c) Conductor

- The topmost filled band is known as the valence band
- The lowermost empty band known as the conduction band
- The gap between valence band and conduction band is known as forbidden energy gap ( $E_g$ )

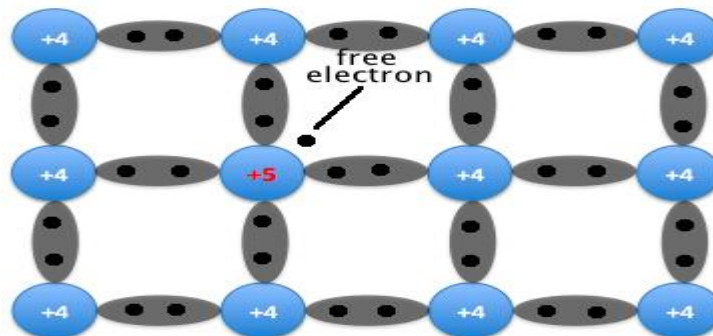
**Unit- 2\_(CO2):** Understand the physics of semiconductor and develop the ability to choose the appropriate semiconductor for engineering applications

Questions	S.No.	Mark
<p>Q-1. Which types of charge carries are available in n-type of semiconductors? Justify your answer.</p> <p><b>Solution:</b> In a pure (intrinsic) Si or Ge semiconductor, each nucleus uses its four valence electrons to form four covalent bonds with its neighbors (see figure below). Each ionic core, consisting of the nucleus and non-valent electrons, has a net charge of +4, and is surrounded by 4 valence electrons. Since there are no excess electrons or holes In this case, the number of electrons and holes present at any given time will always be equal.</p>	1	2



*An intrinsic semiconductor. Note each +4 ion is surrounded by four electrons.*

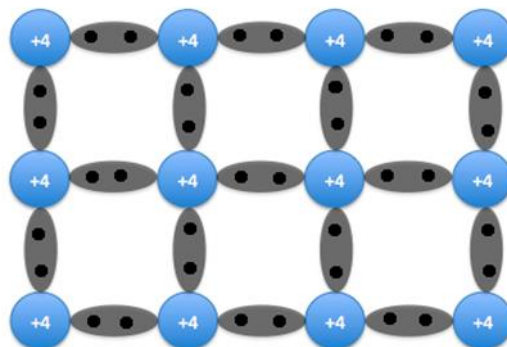
When one of the lattice atoms replace it by an atom with five valence electrons, such as the Group 5 atoms arsenic (As) or phosphorus (P). In this case, the impurity adds five valence electrons to the lattice where it can only hold four. This means that there is now one excess electron in the lattice (see figure below). Because it donates an electron, a Group 5 impurity is called a donor. Note that the material remains electrically neutral.



*A semiconductor doped with a donor. A free electron is now present.*

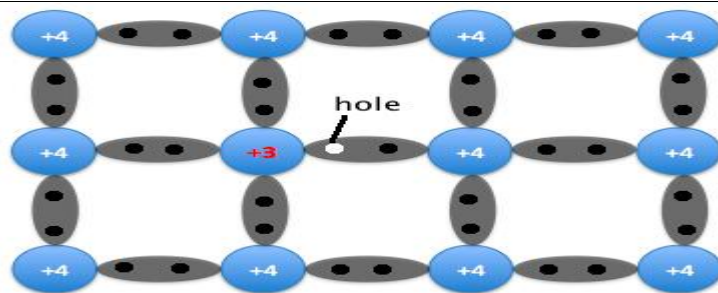
Donor impurities donate negatively charged electrons to the lattice, so a semiconductor that has been doped with a donor is called an n-type semiconductor; "n" stands for negative. Free electrons outnumber holes in an n-type material, so the electrons are the majority carriers and holes are the minority carriers.

Q-2. Which types of charge carries are available in p-type of semiconductors? Justify your answer  
**Solution:** In a pure (intrinsic) Si or Ge semiconductor, each nucleus uses its four valence electrons to form four covalent bonds with its neighbors (see figure below). Each ionic core, consisting of the nucleus and non-valent electrons, has a net charge of +4, and is surrounded by 4 valence electrons. Since there are no excess electrons or holes In this case, the number of electrons and holes present at any given time will always be equal.



*An intrinsic semiconductor. Note each +4 ion is surrounded by four electrons.*

Now, if one of the atoms in the semiconductor lattice is replaced by an element with three valence electrons, such as a Group 3 element like Boron (B) or Gallium (Ga), the electron-hole balance will be changed. This impurity will only be able to contribute three valence electrons to the lattice, therefore leaving one excess hole (see figure below). Since holes will "accept" free electrons, a Group 3 impurity is also called an acceptor.



*A semiconductor doped with an acceptor. An excess hole is now present.*

Because an acceptor donates excess holes, which are considered to be positively charged, a semiconductor that has been doped with an acceptor is called a p-type semiconductor; "p" stands for positive. Notice that the material as a whole remains electrically neutral. In a p-type semiconductor, current is largely carried by the holes, which outnumber the free electrons. In this case, the holes are the majority carriers, while the electrons are the minority carriers.

Q-3. Define the relaxation time and Drift velocity of an electron in a semiconductor

**Solution:** An electron experiences a collision with a probability per unit time  $1/\tau$ . This means that on the average an electron travels for time  $\tau$  after it undergoes a collision and before its next collision

**Relaxation Time:** the average time between two successive collisions is  $\tau$ . This time is known as relaxation time ( $\tau$ ).

The average distance traversed by a free electron between two successive collisions with positive ions is called the mean free path ( $\lambda$ ).

In absence of external electric field, the random motion of free electrons is equally probable in all directions. As a result, there is no net current in the absence of electric field.

**Drift Velocity:** When an external electric field is applied, the electrons are accelerated in a direction opposite to that of electric field. Hence they acquire an average velocity in a direction opposite to that of electric field which is superimposed over the random motion. This velocity is known as the drift velocity ( $v_d$ ).

Q-4. What is the wavelength corresponding to the bandgap of GaAs (1.42eV) approximately?

**Solution:** we know from band theory and quantum theory that ,

$$E_g = hc/\lambda, \text{ therefore}$$

$$\lambda = hc/E_g$$

Where Planck's constant ( $h$ ) =  $6.625 \times 10^{-34}$  J.s. and velocity of light  $C = 3 \times 10^8$  m/s

$$1\text{eV} = 1.6 \times 10^{-19} \text{ joule}$$

$$\lambda = 8.747 \times 10^{-7} \text{ m}$$

$$\lambda = 874.7 \text{ nm}$$

Q-5. Outline the nature of charge on an intrinsic semiconductor on addition of neutral pentavalent or trivalent atoms

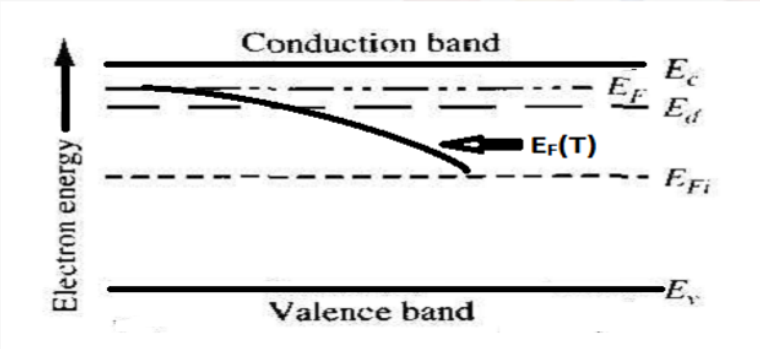
**Solutions:** In a semiconductor, electric charge and hence, electric current is carried by free charge carriers. If free charge carriers are more in number, electric current can flow easily and conductivity of the semiconductor increases.

An intrinsic semiconductor is made up of purely one element which has a valence shell with 4 valence electrons (such as silicon and germanium). These 4 valence electrons bond with 4 valence electrons of their neighbouring atom to complete their octet. Therefore, since the electrons are bound, there is a deficit of free charge carriers.

Pentavalent impurities (like P, As) have 5 electrons in their valence shell. When they are added to an intrinsic semiconductor, 4 electrons of the pentavalent atom bond with 4 electrons of the atom of the semiconductor to form an octet. Thus, one electron remains free and becomes a free charge carrier. This increases the conductivity of the intrinsic semiconductor.

Trivalent impurities (like Ga, In) have 3 valence electrons in their outer shell. When added to intrinsic semiconductors, the 3 electrons try to bond with 4 electrons by breaking bonds and jumping between two

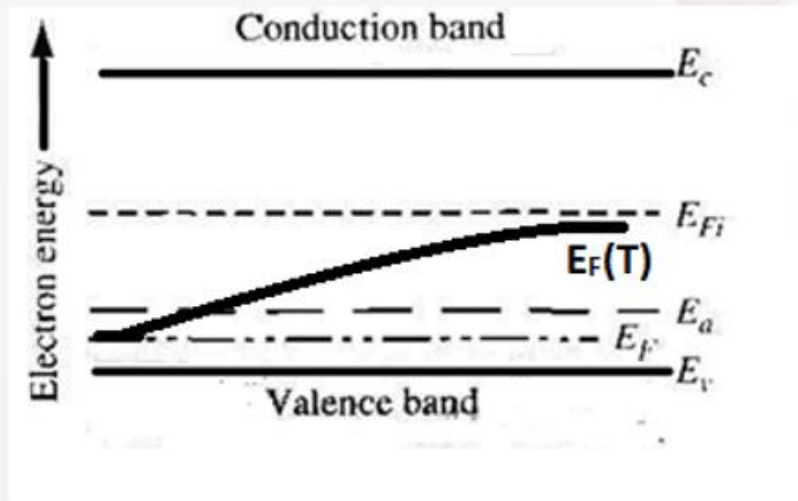


<p>electrons. This results in a void in one of the bonds at all times. This void is known as a hole. Since it is a deficit of electrons, it acts as a positive free charge carrier. This also increases the conductivity of the intrinsic semiconductor.</p> <p>Hence, it is true that addition of either trivalent or pentavalent impurity to an intrinsic semiconductor increases its conductivity.</p> <p>It is note that not only electrons are considered charge carriers in semiconductors and hence, since only pentavalent impurities provide extra electrons, only they increase conductivity. Holes are also considered free charge carriers, as movement of electrons in one direction leads to movement of holes in the other direction, that is, in essence, they carry positive charge in a direction opposite to the negative charge carried by the electrons. Therefore, trivalent impurities also increase the conductivity of an intrinsic semiconductor by providing for the formation of holes in the semiconductor.</p>	
<p>Q-6. Discuss the variation of Fermi- level position with temperature and doping concentration in Extrinsic semiconductors.</p> <p>Solution:</p> <p><b>In n-type semiconductor:</b> At 0 K all allowed energy levels in the valence band are filled by electrons. All donor levels are filled by unbound electrons. The conduction band is free. So charge carriers do not exist, and the semiconductor behaves as an insulator. At 0 K the Fermi level is between the donor levels and the bottom of the conduction band as shown below.</p>  <p><i>Energy level diagram of N-type semiconductor. <math>E_F(T)</math> shows the effect of temperature on Fermi energy</i></p> <p>When the temperature is raised, by absorption of suitable energies, some donor atoms are ionised, so that their electrons are elevated to the conduction band. If the density of ionised donor atom is <math>N_d</math> and the density of electron-hole pairs in the intrinsic semi-conductors is <math>n_i</math> at room temperature T, then <math>N_d \gg n_i</math>. The Fermi energy is given by</p> $E_F = E_C - k T \log_e \left( \frac{N_C}{N_d} \right)$ <p>where <math>N_C = 2 \left[ \frac{2 \pi m_e^* k T}{h^2} \right]^{3/2}</math></p> <p>This shows that in an N-type semiconductor the Fermi-level lies below the bottom of the conduction band. As temperature rises, the Fermi level goes on falling below <math>E_C</math>. When the temperature is sufficiently raised, the electrons and holes generated due to thermal agitation increase significantly and at a stage become fully dominant over the extrinsic carriers. Then the Fermi level approaches the middle of forbidden energy gap.</p> <p><b>In P-type semiconductor:</b> The energy band diagram of a P-type semiconductor is shown in the Figure. The acceptor level is shown by <math>E_a</math> near the top of the valence band, the Fermi level by <math>E_F</math>. At absolute zero, all the holes are in acceptor levels, but as the temperature rises, the electrons from valence band jump into</p>	<p>6</p> <p>2</p>

acceptor level on the absorption of energy ( $E_A - E_V$ ) by each electron. As a result, these electrons are trapped in the acceptor levels and an equal number of holes are created in the valence band. These holes provide conduction currents. At the room temperature, almost all acceptor atoms trap electrons and thus the number of holes available in the valence band is almost equal to the number of impurity atoms added.

The variation of Fermi energy with temperature is given by:

$$E_F = E_V + kT \log_e \left( \frac{N_V}{N_a} \right) \text{ where } N_V = 2 \left[ \frac{2\pi m_h^* kT}{h^2} \right]^{3/2}$$



*Energy diagram of P-type Semiconductor.  $E_F(T)$  shows the effect of temperature on Fermi energy.*

This shows that Fermi level lies above the top of the valence band. The position of Fermi level depends upon the temperature and the number of impurity atoms. When the number of impurity atoms increases, the number of holes in the valence band will increase and the Fermi level will shift towards the valence band. When the concentration of acceptor impurity atoms is sufficiently high, the number of holes will be far greater than the conduction electrons and the Fermi level may even lie in the valence band. As the temperature is sufficiently increased, electrons from the valence band are excited to the conduction band and finally the P-type crystal will start behaving like an intrinsic semi-conductor when the number of electrons in the conduction band will be nearly equal to the valence holes. Thus at extremely high temperatures the Fermi level shifts towards the middle of forbidden energy gap.

Q-7. Distinguish between elemental and compound semiconductors with examples.

Solution: There are different ways of classifying semiconductors depending on the property being measured. One classification that is fairly straight forward is

1.Elemental semiconductors

2.Compound semiconductor

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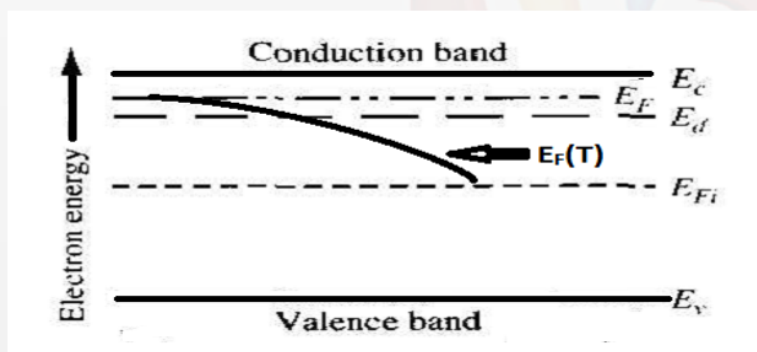
	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A
	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994
	13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065
30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96
48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6
80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium [208.9824]

- Elemental semiconductors (Si and Ge) belong to group IV A of the periodic table. C which is on top of the group is an insulator (diamond) with energy band gap of 5.5 eV while Sn and Pb are metals.
- Compound semiconductors can be formed by combining elements of groups IIIA and VA. Examples include GaAs, GaP, GaN, InSb. AlN is also a III-V but its band gap is around 6.2 eV making it an insulator. Similarly II-VI compound semiconductors can be formed, examples include ZnO, ZnS, CdSe, CdTe.

Q-8. Draw and interpret the graph for the Fermi Energy variation with temperature for P and N type semiconductors.

Solutions:

**In n-type semiconductor:** At 0 K all allowed energy levels in the valence band are filled by electrons. All donor levels are filled by unbound electrons. The conduction band is free. So charge carriers do not exist, and the semiconductor behaves as an insulator. At 0 K the Fermi level is between the donor levels and the bottom of the conduction band as shown below.



Energy level diagram of N-type semiconductor.  $E_F(T)$  shows the effect of temperature on Fermi energy

When the temperature is raised, by absorption of suitable energies, some donor atoms are ionised, so that their electrons are elevated to the conduction band. If the density of ionised donor atom is  $N_d$  and the density of electron-hole pairs in the intrinsic semi-conductors is  $n_i$  at room temperature  $T$ , then  $N_d \gg n_i$ . The Fermi energy is given by

$$E_F = E_C - kT \log_e \left( \frac{N_C}{N_d} \right)$$

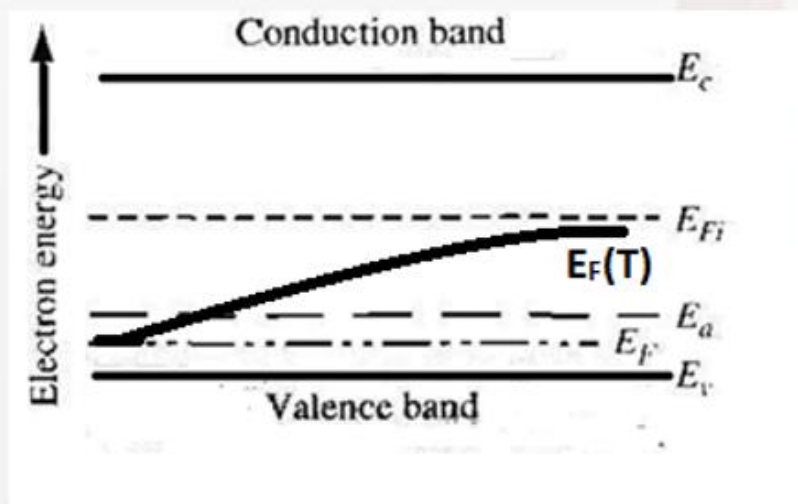
$$\text{where } N_C = 2 \left[ \frac{2\pi m_e^* kT}{h^2} \right]^{3/2}$$

This shows that in an N-type semiconductor the Fermi-level lies below the bottom of the conduction band. As temperature rises, the Fermi level goes on falling below  $E_C$ . When the temperature is sufficiently raised, the electrons and holes generated due to thermal agitation increase significantly and at a stage become fully dominant over the extrinsic carriers. Then the Fermi level approaches the middle of forbidden energy gap.

**In P-type semiconductor:** The energy band diagram of a P-type semiconductor is shown in the Figure. The acceptor level is shown by  $E_a$  near the top of the valence band, the Fermi level by  $E_F$ . At absolute zero, all the holes are in acceptor levels, but as the temperature rises, the electrons from valence band jump into acceptor level on the absorption of energy ( $E_a - E_v$ ) by each electron. As a result, these electrons are trapped in the acceptor levels and an equal number of holes are created in the valence band. These holes provide conduction currents. At the room temperature, almost all acceptor atoms trap electrons and thus the number of holes available in the valence band is almost equal to the number of impurity atoms added.

The variation of Fermi energy with temperature is given by:

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*Energy diagram of P-type Semiconductor.  $E_F(T)$  shows the effect of temperature on Fermi energy.*

This shows that Fermi level lies above the top of the valence band. The position of Fermi level depends upon the temperature and the number of impurity atoms. When the number of impurity atoms increases, the number of holes in the valence band will increase and the Fermi level will shift towards the valence band. When the concentration of acceptor impurity atoms is sufficiently high, the number of holes will be far greater than the conduction electrons and the Fermi level may even lie in the valence band. As the temperature is sufficiently increased, electrons from the valence band are excited to the conduction band

<p>and finally the P-type crystal will start behaving like an intrinsic semi-conductor when the number of electrons in the conduction band will be nearly equal to the valence holes. Thus at extremely high temperatures the Fermi level shifts towards the middle of forbidden energy gap.</p>		
<p>Q-9. Based on band theory of solids, distinguish between conductors, semiconductors, and insulators. The band theory of solids is different from the others because the atoms are arranged very close to each other such that the energy levels of the outermost orbital electrons are affected. But the energy level of the innermost electrons is not affected by the neighbouring atoms.</p> <p>The three energy bands in solids are</p> <ul style="list-style-type: none"> <li>• Valence band</li> <li>• Conduction band</li> <li>• Forbidden band</li> </ul> <p>Bond theory solids</p> <ul style="list-style-type: none"> <li>• In atoms, electrons are filled in respective energy orbits following Pauli's exclusion principle.</li> <li>• In molecules, Two atomic orbitals combine together to form a molecular orbit with two distinct energy levels.</li> <li>• In solids, <math>10^{23}</math> stacked up lines confined in a tiny space would look like a band. Thereby forming energy continuum called energy bands.</li> <li>• This theory helps to visualise the difference between conductor, semiconductors and insulator by plotting available energies for an electron in a material.</li> </ul> <div data-bbox="188 824 1150 1339" data-label="Figure"> </div> <p>Conductors: Metals are conductors in which there is no forbidden energy gap between the conduction band (CB) and valence band (VB). No extra energy required to transfer the electron from VB to CB.</p> <p>Semiconductors: In a semiconductor, the valence band is completely filled with electrons while the conduction band is empty. The energy gap between the bands is less. For electrons to jump from the valence band to the conduction band, room temperature needs to be maintained. If the temperature is OK, there is no transfer of electrons from the valence band to the conduction band.</p> <p>Insulators: In insulators, the valence band is completely filled while the conduction band is empty. This results in a large energy gap. Since the energy gap between the conduction band and the valence band is more, there is no movement of electrons from the valence band to the conduction band.</p>	9	5
<p>Q-10. Define the Fermi energy and Fermi distribution function. Plot the Fermi distribution function at two different temperatures.</p> <p><b>Solution:</b></p> <p>The Fermi-Dirac distribution applies to fermions, particles with half-integer spin which must obey the Pauli Exclusion Principle. It gives the probability, <math>F(E)</math>, for the occupation of a particular energy level <math>E</math> by an electron is given by</p>	10	5



$$F(E) = \frac{1}{1 + \exp[(E - E_F)/k_B T]}$$

At  $T = 0$  K,  $F(E) = 1$  for  $E < E_F$

$F(E) = 0$  for  $E > E_F$

Where  $k_B$  is the Boltzmann's constant,  $T$  is the absolute temperature,  $E$  is the energy of the particular energy level  $E$ , and  $E_F$  is the Fermi energy

It can be seen that for  $T = 0$ , all the states up to energy  $E_F$  are filled with electrons and all the states above  $E_F$  are vacant. At  $E = E_F$  the occupation probability is  $\frac{1}{2}$ .

Thus the Fermi energy can be defined as the energy of the highest filled level at absolute zero. At a finite temperature, the electron may get the energy of order  $k_B T$  and go to higher vacant state, and so

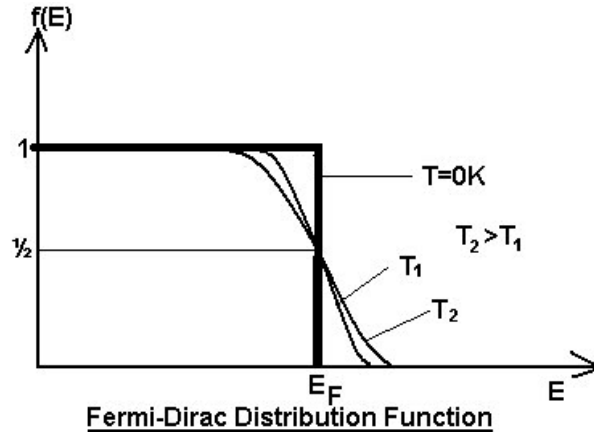


Figure shows the Fermi- function plot at three different temperatures  $\{ T_2 > T_1 > T_0 \}$

Q-11. Distinguish between elemental and compound semiconductors with two examples

**Solution: -Elemental Semiconductors:** *Elemental semiconductors (Si and Ge) belong to group IV A of the periodic table. C which is on top of the group is an insulator (diamond) with energy band gap of 5.5 eV while Sn and Pb are metals.*

		13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A
		5 <b>B</b> Boron 10.811	6 <b>C</b> Carbon 12.011	7 <b>N</b> Nitrogen 14.00674	8 <b>O</b> Oxygen 15.9994
		13 <b>Al</b> Aluminum 26.981539	14 <b>Si</b> Silicon 28.0855	15 <b>P</b> Phosphorus 30.973762	16 <b>S</b> Sulfur 32.066
30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.732	32 <b>Ge</b> Germanium 72.64	33 <b>As</b> Arsenic 74.92159	34 <b>Se</b> Selenium 78.96	
48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.6	
80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.3833	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98037	84 <b>Po</b> Polonium [208.9824]	

**Compound Semiconductors :** Compound semiconductors can be formed by combining elements of groups IIIA and VA. Examples include GaAs, GaP, GaN, InSb. AlN is also a III-V but its band gap is around 6.2 eV making it an insulator. Similarly II-VI compound semiconductors can be formed, examples include ZnO, ZnS, CdSe, CdTe.

Q-12. Distinguish between intrinsic and extrinsic types of semiconductor with examples. Outline the nature of charge in an intrinsic semiconductor on addition of neutral trivalent impurity atoms.

**Solution:** The importance of semiconductors is further increased due to the fact that the conductivity and the effective band gaps of these materials can be modified by the introduction of impurities which strongly affect their electronic and optical properties. The process of introduction of impurities in

semiconductors is called doping. Depending on the nature of impurities added, the semiconductors are classified as :

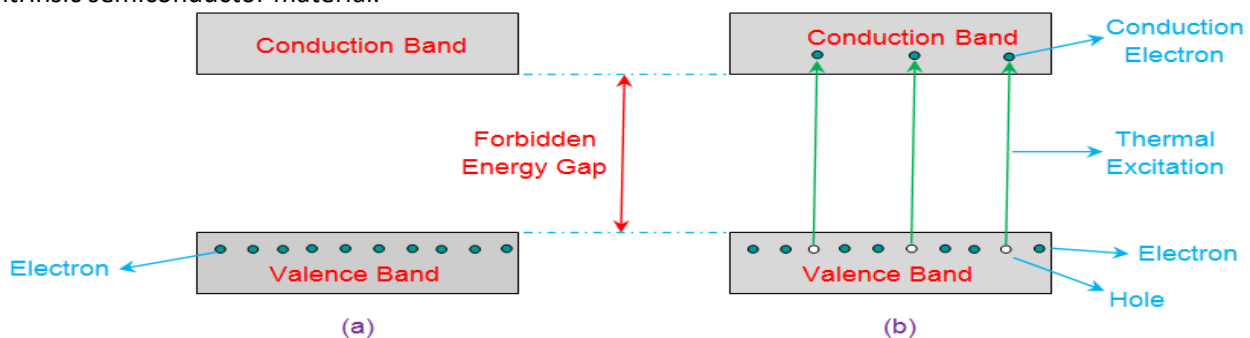
- (a) Pure or intrinsic semiconductors
- (b) Doped or extrinsic semiconductors

The intrinsic semiconductors are pure semiconductors in which no impurity atoms are added. The most common intrinsic semiconductors are Silicon (Si) and Germanium (Ge), which belong to Group IV of the periodic table. The atomic numbers of Si and Ge are 14 and 32, which yields their electronic configuration as  $1s^2 2s^2 2p^6 3s^2 3p^2$  and  $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^2$ , respectively.

This indicates that both Si and Ge have four electrons each in their outer-most i.e. valence shell (indicated by red colour). These electrons are called valence electrons and are responsible for the conduction-properties of the semiconductors. Here it is seen that each valence electron of a Si atom pair with the valence electron of the adjacent Si atom to form a covalent bond.

After pairing, the **intrinsic semiconductor** becomes deprived of free charge carriers which are nothing but the valence electrons. Hence, at 0K the valence band will be full of electrons while the conduction band will be empty (as shown in figure 2 , in next slide). At this stage, no electron in the valence band would gain enough energy to cross the forbidden energy gap of the semiconductor material. **Thus the intrinsic semiconductors act as insulators at 0K.**

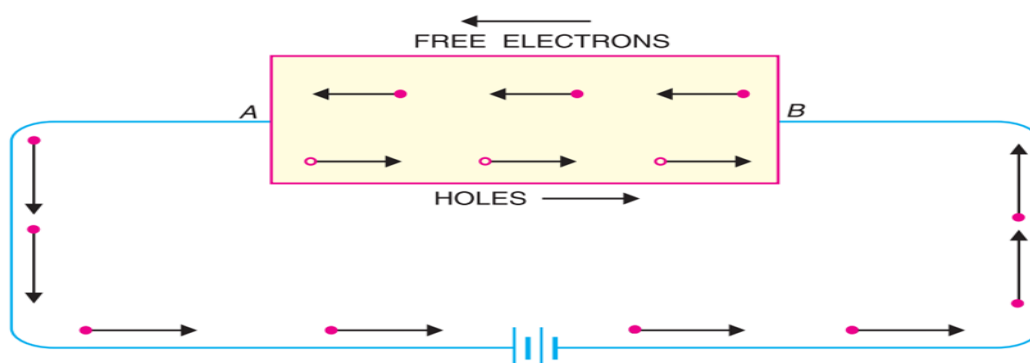
However, at room temperature, the thermal energy may cause a few of the covalent bonds to break, thus generating the free electrons as shown in Figure 3a. The electrons thus generated get excited and move into the conduction band from the valence band, overcoming the energy barrier (Figure 2b). During this process, each electron leaves behind a hole in the valence band. The electrons and holes created in this way are called intrinsic charge carriers and are responsible for the conductive properties exhibited by the intrinsic semiconductor material.



**Figure 2** Energy Band Diagram of Intrinsic Semiconductor at (a) 0K (b) Temperature > 0K

In an intrinsic semiconductor, even at room temperature, hole-electron pairs are created

Under the influence of electric field, conduction through the semiconductor is by both free electrons and holes. Therefore, the total current inside the semiconductor is the sum of currents due to free electrons and holes.



The impurity mixed intrinsic semi-conductors are called extrinsic semiconductor. The process of adding impurity is called doping. The purpose of adding impurities is either to increase the number of free electrons or holes in the semi-conductor crystal.

Depending on the type of impurity added, the extrinsic semi conductor are classified as:

#### **N-type semi-conductors:**

electrons are majority charge carriers.

This is achieved by doping with pentavalent impurity atoms such as Phosphorus.

### P-type semi-conductors:

holes are majority charge carriers.

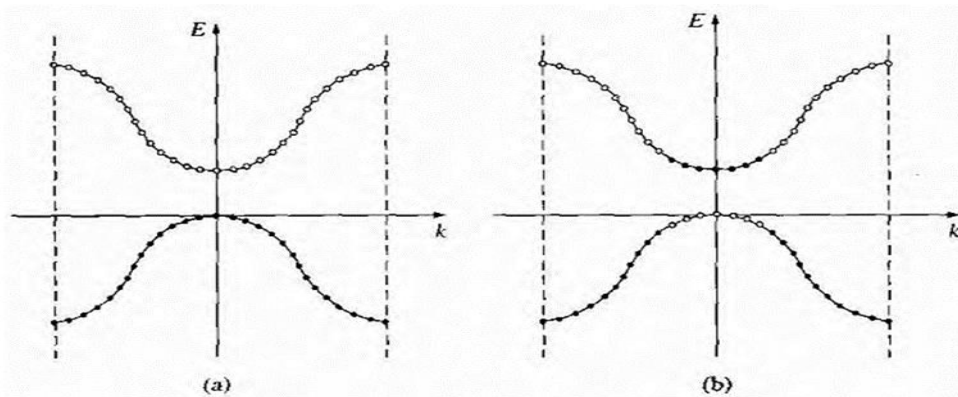
This is achieved by doping with trivalent impurity atoms such as Aluminium

Q-13. Distinguish between the direct and indirect band gap semiconductors with one examples.

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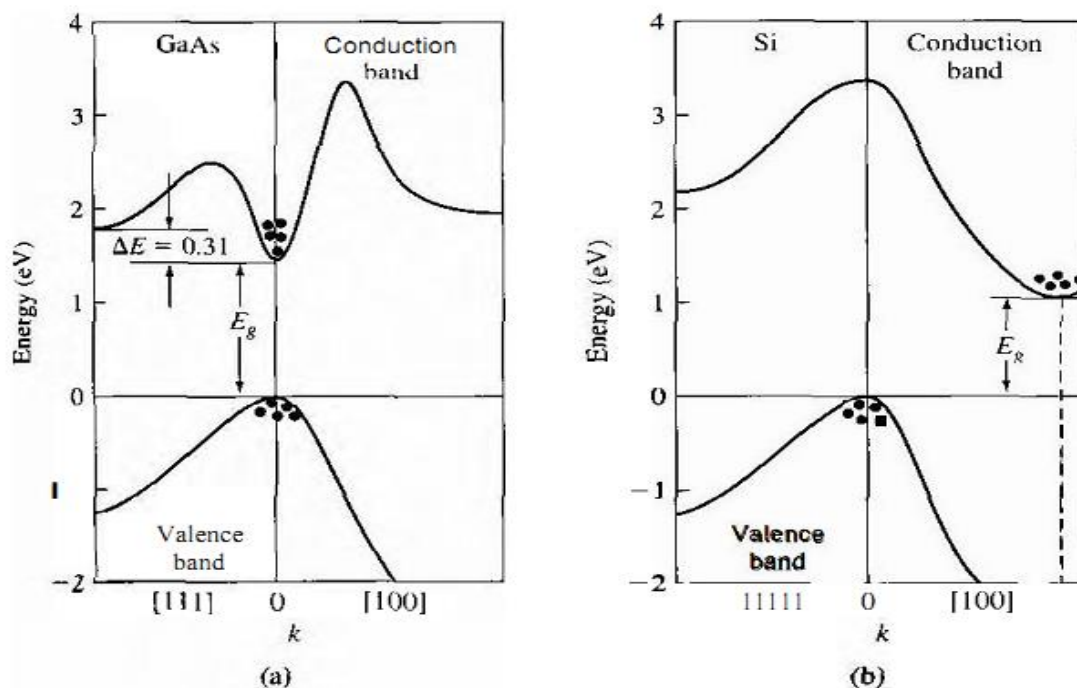
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**Solution:** Figure shows the  $E$  versus  $k$  diagram of the conduction and valence bands for an intrinsic semiconductor at  $T = 0$  K. The energy states in the valence band are completely full and the states in the conduction band are empty. Figure shows these same bands for  $T > 0$  K, in which some electrons have gained enough energy to jump to the conduction band and have left empty states in the valence band. In absence of any external forces, the electron and "empty state" distributions are symmetrical with  $k$ .



The  $E$  versus  $k$  diagram of the conduction and valence bands of a semiconductor at (a)  $T = 0$  K and (b)  $T > 0$  K.

Figure shows the  $E$  versus  $k$  diagram for Ga-As and Si.

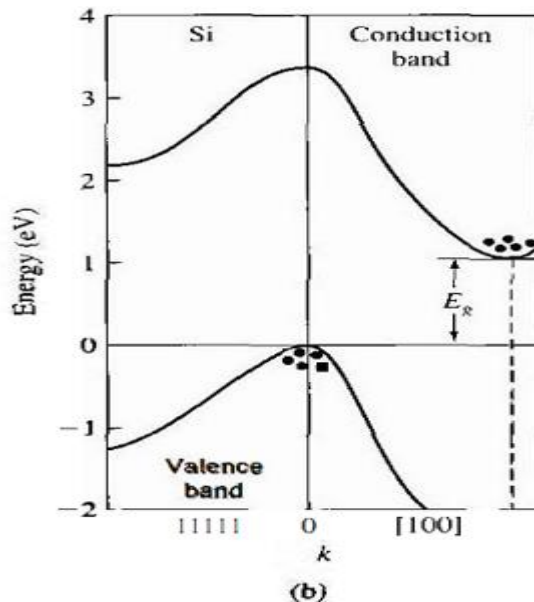


In Ga-As, the valence band maximum and the conduction band minimum both occur at  $k = 0$ . The electrons in the conduction band tend to settle at the minimum conduction band energy which is at  $k = 0$ . Similarly, holes in the valence band tend to congregate at the uppermost valence band energy. In Ga-As, the minimum conduction band energy and maximum valence band energy occur at the same  $k$  value.

**A semiconductor with this property is said to be a direct band gap semiconductor; transitions between the two allowed bands can take place with no change in crystal momentum.** This direct nature has

significant effect on the optical properties of the material. Ga-As and other direct bandgap materials are ideally suited for use in semiconductor lasers and other optical devices.

The E versus k diagram for silicon is shown in Figure b. The maximum in the valence band energy occurs at  $k = 0$  as before. The minimum in the conduction band energy occurs not at  $k = 0$ , but along the [100] direction. The difference between the minimum conduction band energy and the maximum valence band energy is still defined as the bandgap energy. **A semiconductor whose maximum valence band energy and minimum conduction band energy do not occur at the same k value is called an indirect bandgap semiconductor.**



**When electrons make a transition between the conduction and valence bands, we must invoke the law of conservation of momentum. A transition in an indirect bandgap material must necessarily include an interaction with the crystal so that crystal momentum is conserved.** Germanium is also an indirect bandgap material, whose valence band maximum occurs at  $k = 0$  and whose conduction band minimum occurs along the [111] direction. GaAs is a direct bandgap semiconductor, but other compound semiconductors such as GaP and AlAs, have indirect bandgaps.

Q-14. Describe the P and N types semiconductors and indicate the Fermi level and energy level of impurity atoms in band diagram

**Solution:** Depending on the type of impurity added, the extrinsic semiconductor are classified as:

**N-type semi-conductors:**

electrons are majority charge carriers.

This is achieved by doping with pentavalent impurity atoms such as Phosphorus.

**P-type semi-conductors:**

holes are majority charge carriers.

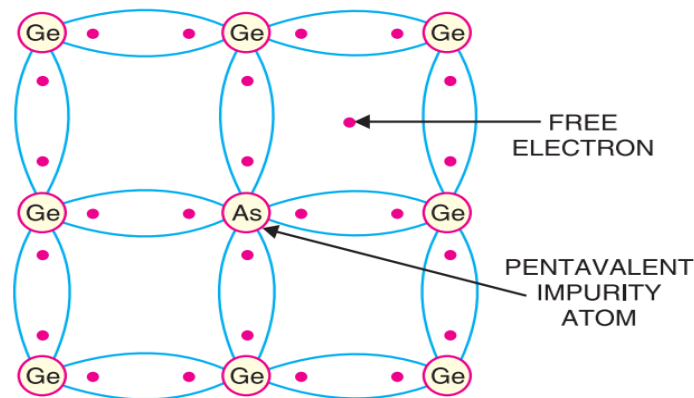
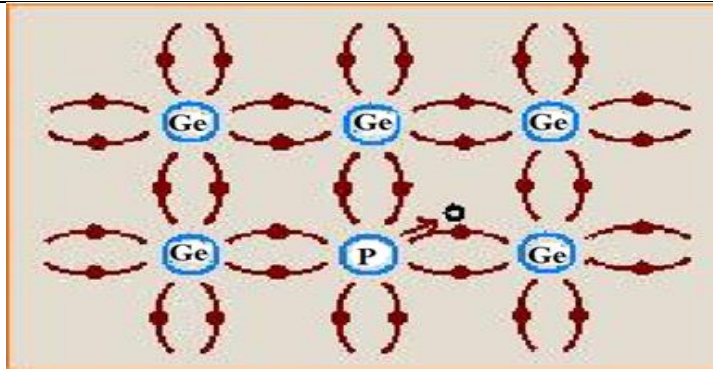
This is achieved by doping with trivalent impurity atoms such as Aluminium.

When a small amount of pentavalent impurity (phosphorus, bismuth, arsenic, antimony) is doped in pure semi-conductor then the conductivity of crystal increases due to surplus electrons and such a doped semi-conductor is called N-type semi-conductors while the impurity atoms are called donors, because they donate free electrons for conduction to the semiconductor crystal.

To explain the formation of N-type semiconductor, consider that a pentavalent impurity phosphorus is added to a pure germanium crystal. Each impurity atom with five valence electrons replaces a germanium atom. The four valence electrons of impurity atom form covalent bonds with electrons of neighbouring germanium atoms, while the fifth electron becomes surplus. Therefore for each impurity atom added one electron will be available for germanium crystal to cause conduction.

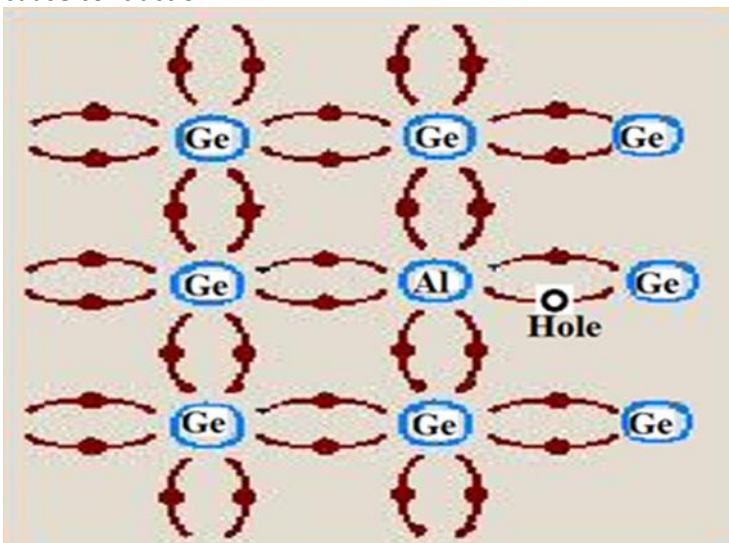
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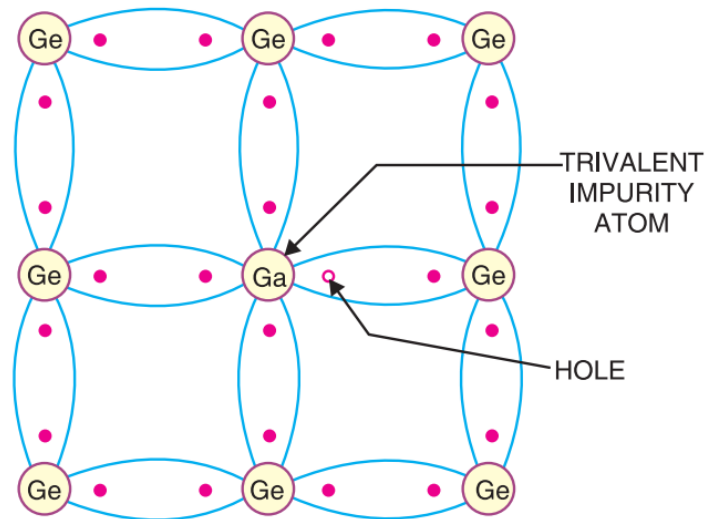


When a small amount of trivalent impurity like gallium, indium, aluminium or boron is doped in a pure semi-conductor, then the conductivity of crystal increases due to the deficiency of electrons (i.e., holes) and such a doped semi-conductor is called P-type semi-conductors, while the impurity atoms are called acceptors because the holes created can accept the electrons.

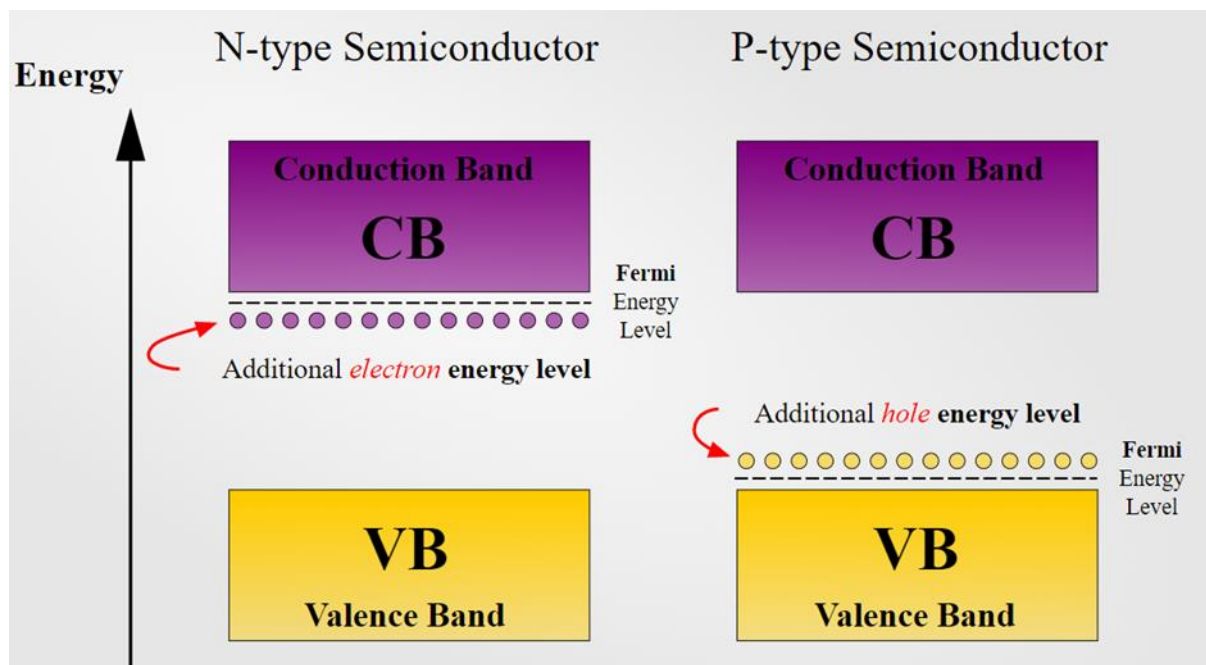
To explain the formation of P-type semi-conductor, consider that a trivalent impurity (Aluminium or Ga) is added to pure germanium crystal. Each impurity atom with three valence electrons replaces a germanium atom. Three valence electrons of Aluminium can form only three single covalent bonds with neighbouring germanium atoms. In the formation of fourth covalent bond there is a deficiency of electron with Aluminium. This deficiency acts like a positive charge and is called a hole. Therefore for each impurity atom added, a hole is created. A small amount of trivalent impurity provides millions of holes to cause conduction.







Fermi level and impurity atoms (Donor/ Acceptors) level in n type and p-type of semi-conductors



Q-15. Explain the extrinsic semiconductor. Using suitable diagram, discuss how the Fermi level changes with change of temperature in extrinsic semiconductors.

**Solution:**

**Extrinsic Semiconductors (Definition)** - An extrinsic semiconductors are those semiconductors that come into existence when a measured and small amount of chemical impurity is added to intrinsic semiconductors. It is also known as doped semiconductor or impurity semiconductors. The doping of the semiconductors increases its conductivity. The process of deliberately adding a desirable impurity is known as doping and the impurity atoms are called dopants. Extrinsic semiconductors are further classified into two types - N-Type semiconductors and P-type semiconductors.

At lower temperatures the quasi Fermi level is between conduction and donor energy level for n type semiconductor and between valence and acceptor energy level for a p type semiconductor but as temperature increases gradually, the quasi Fermi level falls in case of n type and rises gradually in case of p type semiconductor and after a certain temperature, the quasi fermi level becomes equal to half of the band gap of the semiconductor and at that point, the quasi Fermi level is same as the Fermi level for an intrinsic one and hence, the extrinsic semiconductor acts as an intrinsic one.

# The Fermi Level: Extrinsic Semiconductor

## Fermi Level Position: Extrinsic Semiconductor

We can now determine the position of the Fermi energy level as a function of the doping concentrations.

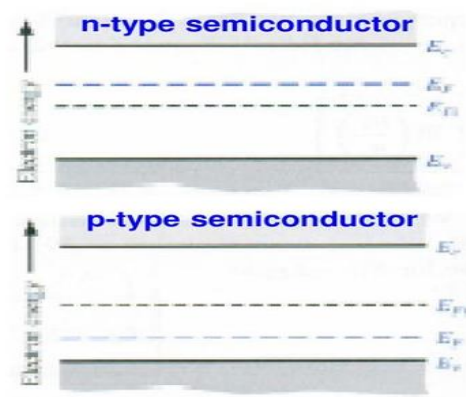
For n-type semiconductor

$$n_0 = N_C e^{-(E_C - E_F)/kT} \approx N_D$$

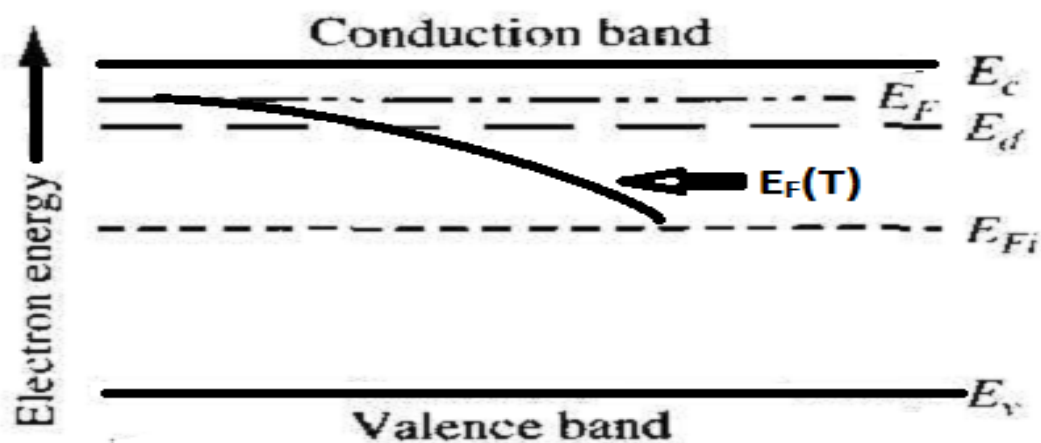
$$\Rightarrow E_C - E_F = kT \ln \left( \frac{N_C}{N_D} \right)$$

For p-type semiconductor

$$E_F - E_V = kT \ln \left( \frac{N_V}{N_A} \right)$$



**In n-type semiconductor:** At 0 K all allowed energy levels in the valence band are filled by electrons. All donor levels are filled by unbound electrons. The conduction band is free. So charge carriers do not exist, and the semiconductor behaves as an insulator. At 0 K the Fermi level is between the donor levels and the bottom of the conduction band as shown below.



*Energy level diagram of N-type semiconductor.  $E_F(T)$  shows the effect of temperature on Fermi energy*

When the temperature is raised, by absorption of suitable energies, some donor atoms are ionised, so that their electrons are elevated to the conduction band. If the density of ionised donor atom is  $N_d$  and the density of electron-hole pairs in the intrinsic semi-conductors is  $n_i$  at room temperature  $T$ , then  $N_d \gg n_i$ . The Fermi energy is given by This shows that in an N-type semiconductor the Fermi-level lies below the bottom of the conduction band. As temperature rises, the Fermi level goes on falling below  $E_C$ . When the temperature is sufficiently raised, the electrons and holes generated due to thermal agitation increase significantly and at a stage become fully dominant over the extrinsic carriers. Then the Fermi level approaches the middle of forbidden energy gap.

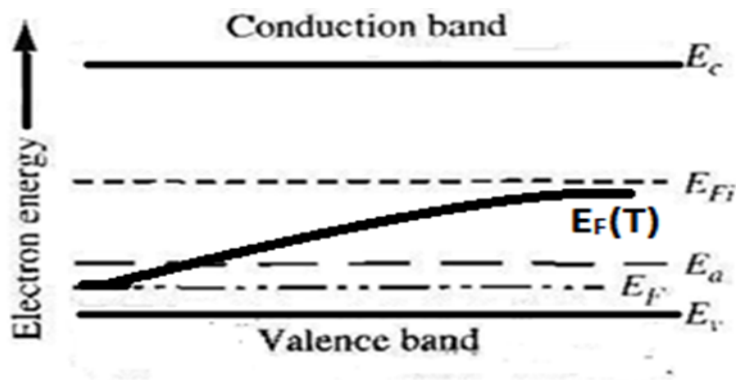
$$E_F = E_C - kT \log_e \left( \frac{N_C}{N_d} \right)$$

$$\text{where } N_C = 2 \left[ \frac{2\pi m_e^* kT}{h^2} \right]^{3/2}$$

**In P-type semiconductor:** The energy band diagram of a P-type semiconductor is shown in the Figure. The acceptor level is shown by  $E_a$  near the top of the valence band, the Fermi level by  $E_F$ . At absolute zero, all the holes are in acceptor levels, but as the temperature rises, the electrons from valence band jump into acceptor level on the absorption of energy ( $E_a - E_v$ ) by each electron. As a result, these electrons are trapped in the acceptor levels and an equal number of holes are created in the valence band. These holes provide conduction currents. At the room temperature, almost all acceptor atoms trap electrons and thus the number of holes available in the valence band is almost equal to the number of impurity atoms added.

The variation of Fermi energy with temperature is given by:

$$E_F = E_V + kT \log_e \left( \frac{N_V}{N_a} \right) \text{ where } N_V = 2 \left[ \frac{2\pi m_h^* kT}{h^2} \right]^{3/2}$$



Energy diagram of P-type Semiconductor.  $E_F(T)$  shows the effect of temperature on Fermi energy.

This shows that Fermi level lies above the top of the valence band. The position of Fermi level depends upon the temperature and the number of impurity atoms. When the number of impurity atoms increases, the number of holes in the valence band will increase and the Fermi level will shift towards the valence band. When the concentration of acceptor impurity atoms is sufficiently high, the number of holes will be far greater than the conduction electrons and the Fermi level may even lie in the valence band. As the temperature is sufficiently increased, electrons from the valence band are excited to the conduction band and finally the P-type crystal will start behaving like an intrinsic semi-conductor when the number of electrons in the conduction band will be nearly equal to the valence holes. Thus at extremely high temperatures the Fermi level shifts towards the middle of forbidden energy gap.